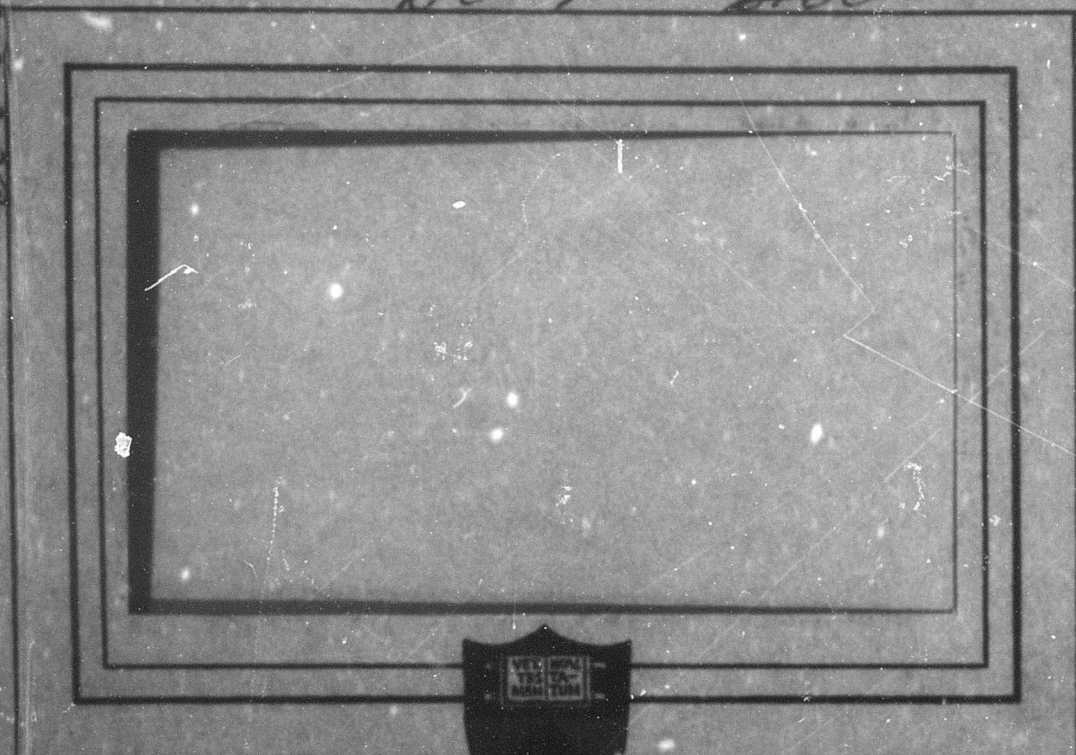


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FURTHER DEVELOPMENT OF A GRAPHITE HEATER
FOR HIGH PRESSURE NITROGEN OPERATION

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Report 669

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ACKNOWLEDGEMENT

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ABSTRACT

An experimental study was conducted to extend the operation of a graphite resistance nitrogen heater to pressures above the 1000 psi previously obtained. Using a somewhat modified design, a single pass spiral heater element was fabricated and tested at 5000 psi and 5000° R. Test runs of 5 to 15 minutes were carried out with total operating times at elevated temperatures and pressure exceeding several hours using the same element. The temperature was determined by the mass flow technique and checked against a thermocouple installed in the stagnation chamber. ()

(SEE ALSO PT-157 424)

NOMENCLATURE

| | |
|----------------|--|
| \dot{m} | Mass flow rate |
| P_o | Stagnation pressure |
| A_* | Throat area |
| γ | Specific heat ratio |
| R | Gas constant |
| Γ | Function of γ |
| $\bar{\Gamma}$ | Mean value of Γ from stagnation chamber to throat |
| ω | Turbine frequency |
| T_o | Stagnation temperature |

SUBSCRIPTS

| | |
|-----|-----------------------|
| c | Cold gas condition |
| h | Hot gas condition |
| o | Stagnation conditions |
| $*$ | Throat conditions |

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I. INTRODUCTION

During the past decade, several concepts have been utilized to obtain wind tunnels which operate at hypersonic speeds. For Mach numbers up to about 12, the conventional storage type or direct electrical heater is available. However, for Mach numbers above 12, there is considerable difficulty due to the high temperature and high pressure stagnation conditions. Several types of facilities exceed $M \sim 12$ by restricting their operation to very short run times and thus avoid the continuous operation problems of the stagnation chamber (hot shot and shock tunnels). Other types which have long run times (the arc-tunnel and plasma wind-tunnel) are restricted to low pressure operation and have not been able to operate at Mach numbers above 12.

Some time ago a study was undertaken at the Gas Dynamics Laboratory to develop a hypersonic wind-tunnel which would operate at elevated temperatures and pressures using a gas with characteristics similar to that of air. Such a wind-tunnel was developed in 1960 using nitrogen as the test gas and a resistance heater made from graphite. The first development provided a capability of operating a wind-tunnel with stagnation conditions of 1000 psia and 5000° R. continuously. Several reports have outlined these early results (Ref. 1-4). The purpose of the present report is to present some of the further work which has taken place to extend the operation of the heater to higher pressures.

II. TEST EQUIPMENT

The major pieces of equipment used in the present series of tests were taken from the pilot hypersonic nitrogen facility. (Ref. 1). Modifications in the heater design, mounting and instrumentation, were necessary to cope with the higher gas pressure, cooling and precision of measurement requirements. A line diagram of the high pressure, high temperature nitrogen test rig is shown in Fig. 1.

Nitrogen was obtained in trailers at an initial pressure level of 2400 psia. The nitrogen specifications limited the oxygen content to 8 parts per million or less with the water content less than 1 part per million. The nitrogen could be used directly from the trailer or could be boosted by the use of diaphragm compressors to as high as 15,000 psia.

The pressure in the tank which contained the heater element was controlled by a Hammel-Dahl valve used in conjunction with a Moore positioner and Bristol controller. Between the control valve and high pressure tank was located the flow rate system which could be bypassed by operation of two high pressure Barksdale shear seal valves, one manually operated, the other solenoid operated. The flow rate system consisted of a gas filter, a thermocouple assembly and turbine flow meter. The filter is used primarily to keep large particles from getting into contact with the turbine flow meter. A copper-constantan thermocouple assembly was constructed to measure the gas temperature ahead of the turbine flow meter. A calibrated Potter turbine flow meter capable of operating at pressures up to 10,000 psi was used to measure the volume flow rate (which is related to the mass flow rate). The rate of which the turbine rotates is indicated by a counter. In the previous work, at low pressure, a float type flow meter was employed.

After the flow meter, the gas enters the pressure tank. The gas enters the heater element at one end, passes through a spiral passageway in the element, enters a small stagnation region, then through the water cooled copper throat into the diverging section of a nozzle. The conical nozzle had a throat diameter of 0.032 inches and a final diameter of 3.00 inches. The throat and nozzle combination was made to simulate the future detailed design of a hypersonic nozzle. No attempt was made in these tests to evaluate flow conditions in the nozzle.

The pressure in the stagnation chamber formed by a short cylindrical section in the nozzle block ahead of the throat just downstream of the heater element is measured by a Heise gauge. The difference in pressure between the tank and stagnation pressure is measured by a Barton differential pressure gauge with a full scale reading of 400 psi. The millivolt output of thermocouples located ahead of the flow meter and in the stagnation chamber are read on a Rubicon potentiometer. A photograph of the pressure vessel, nozzle, and diffuser is shown in Fig. 2.

The details of the pressure vessel are shown in Fig. 3. The chamber is enclosed at the cold end by a stainless steel recessed head and at the hot end by a flanged section bolted to the tank. At the cold end, a stainless steel holder passes through the head but is insulated from it by a thin film of epoxy resin. A brass tube which carries the current as well as water for cooling purposes passes through the holder. The cold end of the heater is connected to the stainless steel holder by a nut which tightens the element against two sets of graphite collets. A seal is made between the heater element and nozzle by means of a copper O-ring. A cylindrical pyrolytic graphite radiation shield around the heater element

was used to prevent radiation heating of the tank walls. The nozzle block, made from a single piece of high purity copper, acts as the hot end closure of the tank, the electrical contact for the graphite element, and the structural and heat sink material in which the small settling chamber, converging section, throat and conical expansion region are machined. Cooling of this copper block is provided primarily to prevent overheating of the steel end cap and pressure tank. Cooling of the throat section is by pure radial and axial conduction.

The graphite heater element is made in two parts, a spindle (into which a spiral passage is cut), and an outer shell (Fig. 4). The two parts are carefully machined to give contact along their entire length when press-fitted together. The final element design shown differs in small detail from the units used in Ref. 1-4 to improve the temperature distribution along the element and to strengthen and simplify the element. The slotted hot end, which replaces a series of small radial orifices and the tapered outer shell are the major modifications. The gas enters the heater through a blind end hole at the cold end of the spindle. Four radial holes connect the entering passage to the spiral path down the element. A slotted or fluted section, which removes the swirl, then leads to the small stagnation chamber. The stagnation chamber is $3/16$ inches diameter and $1/8$ inch long. A stagnation temperature thermocouple was located as shown in Fig. 5. The butt welded thermocouple of tungsten-tungsten 26% rhenium wires, 0.010 inches in diameter was held in position and sealed with sauerelsen cement.

III. STAGNATION TEMPERATURE MEASUREMENT

The temperature of the gas in the stagnation chamber is required to evaluate the heater performance and the subsequent expansion process in the nozzle. Several methods can be used to determine temperatures in the range of 5000° R. but only three methods will be considered here.

As it is somewhat difficult to measure the temperature of a gas directly at these high values (5000° R.) an indirect method of gas temperature determination was sought. If it is possible to measure the mass flow of the gas, the temperature can be calculated. The well known equation for the flow of a perfect gas in thermodynamic equilibrium through a sonic orifice is

$$\dot{m} = \frac{P_0 A_*}{\sqrt{T_0}} \left\{ \frac{\gamma}{R} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \right\}^{\frac{1}{2}} \quad (1)$$

Where

P_0 - stagnation pressure ahead of the sonic orifice

T_0 - stagnation temperature ahead of the sonic orifice

A_* - area of the sonic orifice

γ - specific heat ratio of the gas

and R - the gas constant

With this basic equation for the mass flow, the temperature of a hot gas can be calculated by two indirect methods.

A. METHOD A

The basic equation for the mass flow can be simplified to the following

$$\dot{m} = \frac{\Gamma P_0 A_*}{\sqrt{R T_0}} \quad (2)$$

where

$$\Gamma = \left[\gamma \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{\frac{1}{2}}$$

If the gas is passed through a sonic orifice cold (room temperature) as well as hot, at the same pressure, then

$$\frac{\dot{m}_c}{\dot{m}_h} = \frac{\left[\frac{\Gamma A_*}{\sqrt{T_o}} \right]_c}{\left[\frac{\Gamma A_*}{\sqrt{T_o}} \right]_h}$$

The value of Γ is constant for a perfect gas, but under the conditions of the present tests, pressures higher than 1000 psia and gas temperatures varying from room temperature to 5000°R., the nitrogen must be considered as a real gas (Ref. 5). The variation of Γ with pressure over the restricted temperature range of -50°C. to 50°C. is shown in Fig. 6. The variation of Γ can be from 0.70 to 0.77 with γ varying from 1.55 to 1.98. At elevated temperature, Γ is independent of pressure. The variation of Γ is from 0.674 at 2000°R. to 0.665 at 6000°R. with a corresponding change of γ from 1.353 to 1.290.

In this method of temperature determination, it is not necessary to know the dimension of the throat, but merely to assume that the throat is unaltered by hot or cold gas flow through it. If this is done at the same pressure, then

$$\frac{\dot{m}_c}{\dot{m}_h} = \frac{\Gamma_c}{\Gamma_h} \sqrt{\frac{T_{oh}}{T_{oc}}} \quad (3)$$

The values of \dot{m}_c , \dot{m}_h are measured by a mass flow meter and T_{oc} is

measured by a suitable thermocouple. The value of \bar{T} is the average of the chamber and throat values. The value of \bar{T} cold can vary as much as 2% from the chamber and throat value (see Fig. 6). The value of \bar{T}_h can vary as much as 0.25% from the chamber and throat value.

This method was not utilized in the evaluation of $\dot{m}_{o,h}$ because of the inaccuracy involved in the calculation of \bar{T}_c . In addition, the mass flow meter has a restricted range over which it is accurate. In the present system it could be used for hot gas flows over the entire pressure range but could not be used to measure cold gas flows at pressures over 3500 psia as the mass flow through the turbine flow meter would have exceeded the operating conditions for the meter. An important consideration in the method is that no accurate measurement of the throat diameter is required.

B. METHOD B

The basic equation of the mass flow was simplified to

$$\dot{m}_h = \left[\frac{\Gamma}{\sqrt{R}} \frac{P_o A_*}{\sqrt{T_o}} \right]_h$$

In this case only hot gas conditions are considered with the mass flow being the only term measured at high pressure and low temperature. This mass flow would require a knowledge of the pressure and temperature of the gas ahead of the flow meter. The value of \dot{m}_h would vary in the small range from 0.676 to 0.6654 over the temperature range 2000° R. to 6000° R.

A measurement is made of the throat diameter at room temperature, to be used in the calculation of the throat area (hot). It is implied that the throat area is unaffected by hot gas flow. It is very

important to measure the throat diameter accurately as the estimated hot gas temperature varies as (diameter)⁴. The throat measurement was made to better than $\pm 1\%$. The only other quantity required in the calculation of the gas temperature is the value of the stagnation pressure which can be measured quite accurately.

This method was used in the determination of the gas temperature. The quantities required for the calculation of the temperature can be measured quite directly and more accurately than in method A.

The first two methods outlined require an accurate determination of the mass flow through the system. The method used was to determine the local density (from measured pressure and temperature) and then calculate the mass flow by measuring the volume flow using a Potter turbine flow meter. The meter had a frequency output which was

$$1 \text{ cps} = 1.3399 \times 10^{-5} \text{ cu. ft./sec.}$$

and therefore the mass flow was simply

$$\dot{m} = \left(\frac{\rho}{\rho_0} \right) \rho_0 [1.3399 \times 10^{-5} \omega]$$

where ρ_0 is the density of nitrogen at 0°C. and 1 atmosphere pressure and ω is the frequency at which the turbine rotated as indicated by the counter.

IV. THERMOCOUPLE MEASUREMENT

The temperature of a gas can be obtained by a third method which is a direct measurement of the gas temperature by means of a thermocouple. High temperature thermocouples have recently been developed which will withstand temperatures of 5500°R. in a non-oxidizing atmosphere with fairly good repeatability. The couple employed in the present system was a tungsten-tungsten/26% rhenium junction. The 0.010 inch diameter wires were purchased from Englehard Industries with a calibration curve supplied by the company. It should be pointed out that the output of the couple is not linear over the temperature range.

V. RESULTS

The primary purpose of the present work was to assess the performance of a heater element at pressures above 1000 psi. and temperatures of about 5000° R. The first part of the study was associated with progressive tests to higher and higher pressures starting with heater elements developed in Refs. 1 through 4. Analysis of the results of these tests and failure of heater elements under these more severe conditions, resulted in several modifications to the heater element design and construction with the final design shown in Fig. 4. This design of the heater element was tested extensively at pressures of 3000, 4000 and 5000 psi. and for testing times, from 5 to 15 minutes. A single heater element of the final design was used for all of these tests with the total running time being well over five hours on this element with no sign of incipient failure. A test run consisted of passing gas through the heater to about 2000 psia, at which time the power was turned on. The pressure and temperature were then increased to their required values. A record was made of the mass flow, stagnation chamber thermocouple and power readings during the test run. The tunnel was shut down by decreasing the power level to the graphite element but continuing to pass nitrogen through the tunnel to cool off the internal components. The basic determination of the temperature was made from measurements of the mass flow under hot conditions with the basic assumption of constant throat area being implicit in the calculation.

The direct measurement of the stagnation temperature was attempted by using the thermocouple noted above. It should be pointed out, however, that one would expect that such a thermocouple would always read temperatures lower than the actual gas temperature because of several very

Important corrections. First, the thermocouple was placed in a gas path where it was exposed to both the radiation from the bottom of the heater, and also was exposed to the cold walls of the copper nozzle block directly below it. (see Fig. 5). In addition, the thermocouple wires themselves provided a path along which heat could be conducted from the thermocouple junction. A comparison of the hot gas temperatures as measured by the thermocouple and by the mass flow technique is shown in Fig. 7. The thermocouple and mass flow temperatures are in good agreement up to about 3000°R. and deviate above this point. At temperature of 5000°R. , the thermocouple read some 1000°R. less than the temperature determined by the mass flow method. The results show a small effect of pressure level in the stagnation chamber. In general, the higher pressures gave higher thermocouple temperatures than the lower pressure readings at the same mass flow temperature. This might be expected since the increased density would result in higher convection heating of the thermocouple.

A calculation of the approximate losses from the thermocouple junction, due to conduction and radiation, was carried out. This calculation could not be carried out to a high order of accuracy because of the limited data as to the temperature distribution along the thermocouple wires, the emissivity of the wire and to the exact temperature of the rather complicated configuration to which the wire radiated. The primary contribution was, of course, the cold nozzle walls. The combination of the radiation and conduction effects resulted in an estimated correction of about 1000°R. about the difference found in comparing the thermocouple results with the mass flow measurements.

Some indication of the efficiency of the heater could be determined by calculating the energy input into the heater calculated from

the measured current and voltage and comparing it with the energy put into the gas as computed from the stagnation temperature. The power input results for three stagnation pressures over a range of stagnation temperatures is shown in Fig. 8. For the present studies, a maximum power input to the element of about 40 KW was achieved. From these curves the efficiency of the heater (power to the gas divided by the electrical power into the heater) is of the order of 85%, a very high value when compared to the general performance of arc or plasma heaters.

VI. CONCLUDING REMARKS

The present study of graphite heater elements for high pressure and temperature operation, has resulted in a modified element design which has operated satisfactorily at pressures of 5000 psi and temperatures as high as 5000° R. continuously. Studies of the final element configuration were carried out in a series of tests varying in time from 5 to 15 minutes with the total hot testing time at high pressures and high temperatures exceeding five hours.

The use of a tungsten-tungsten 26% rhenium thermocouple provides a method of directly measuring the temperature in the stagnation region, but conduction and radiation errors result to as much as 1000° R. at the high temperature end of the study. Agreement between the thermocouple reading and the mass flow temperature measurement used were reasonable up to about 3000° R. with deviations above this point being due to radiation losses and conduction along the thermocouple wires.

Operation at the high pressure and temperature levels of the present work seems to indicate that further plans to extend operation to stagnation pressures of 10,000 psi. are quite reasonable. The changes required to go from 1000 to 5000 psi. have been restricted only to details of the heater design, and problems of instrumentation and operation. The use of a conduction cooled copper throat has still been adequate for the present circumstances and this point appears to be the possible crucial limitation in going to higher stagnation pressures. Higher stagnation pressures might also be expected to be more conducive to higher temperature tests, and although results herein have only been reported to 5000° R., operation at 5700° R. at 5000 psi. have also been carried out with no detrimental heater effects. At high pressures, temperatures in excess of 6000° R. appear to be quite feasible.

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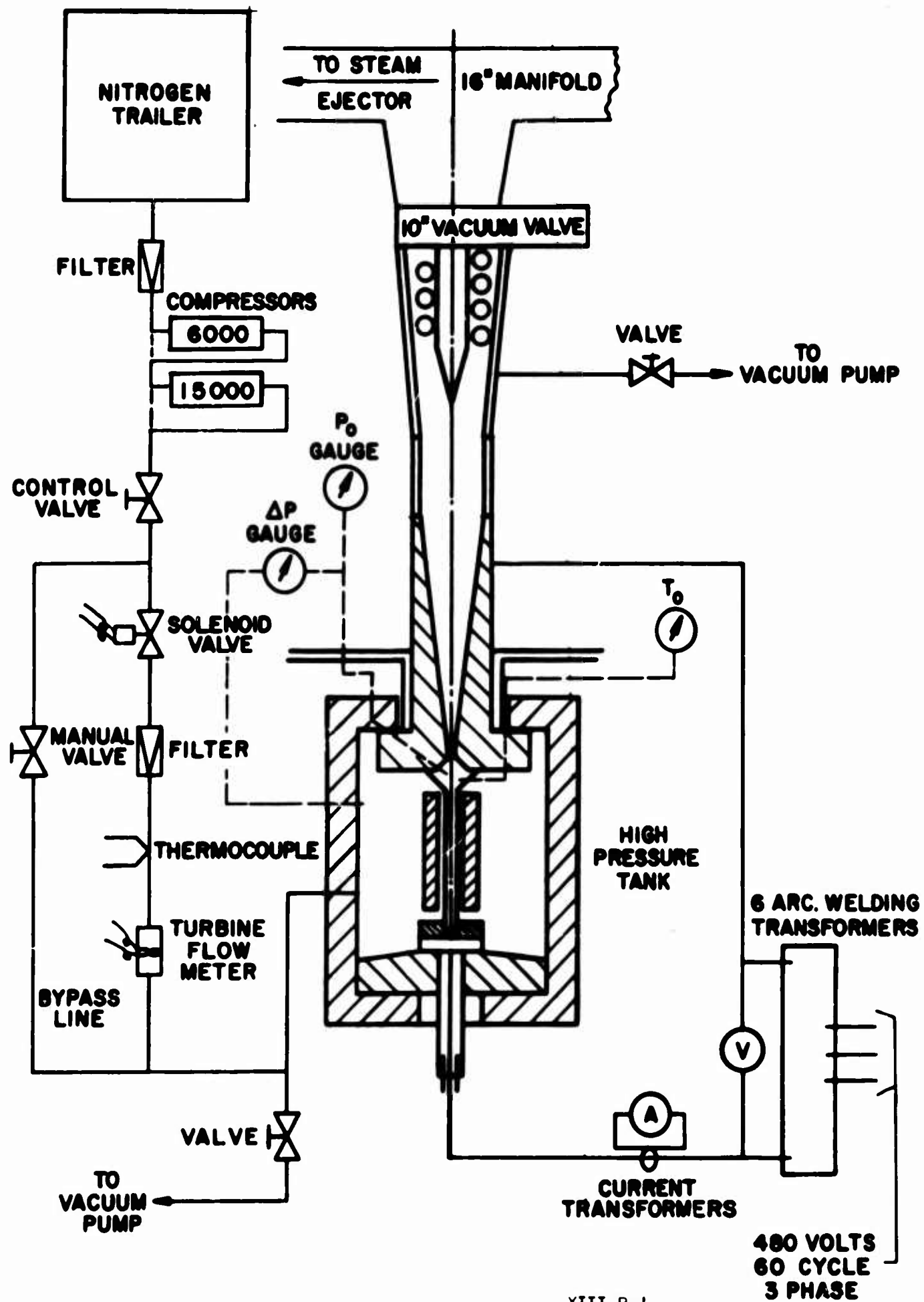
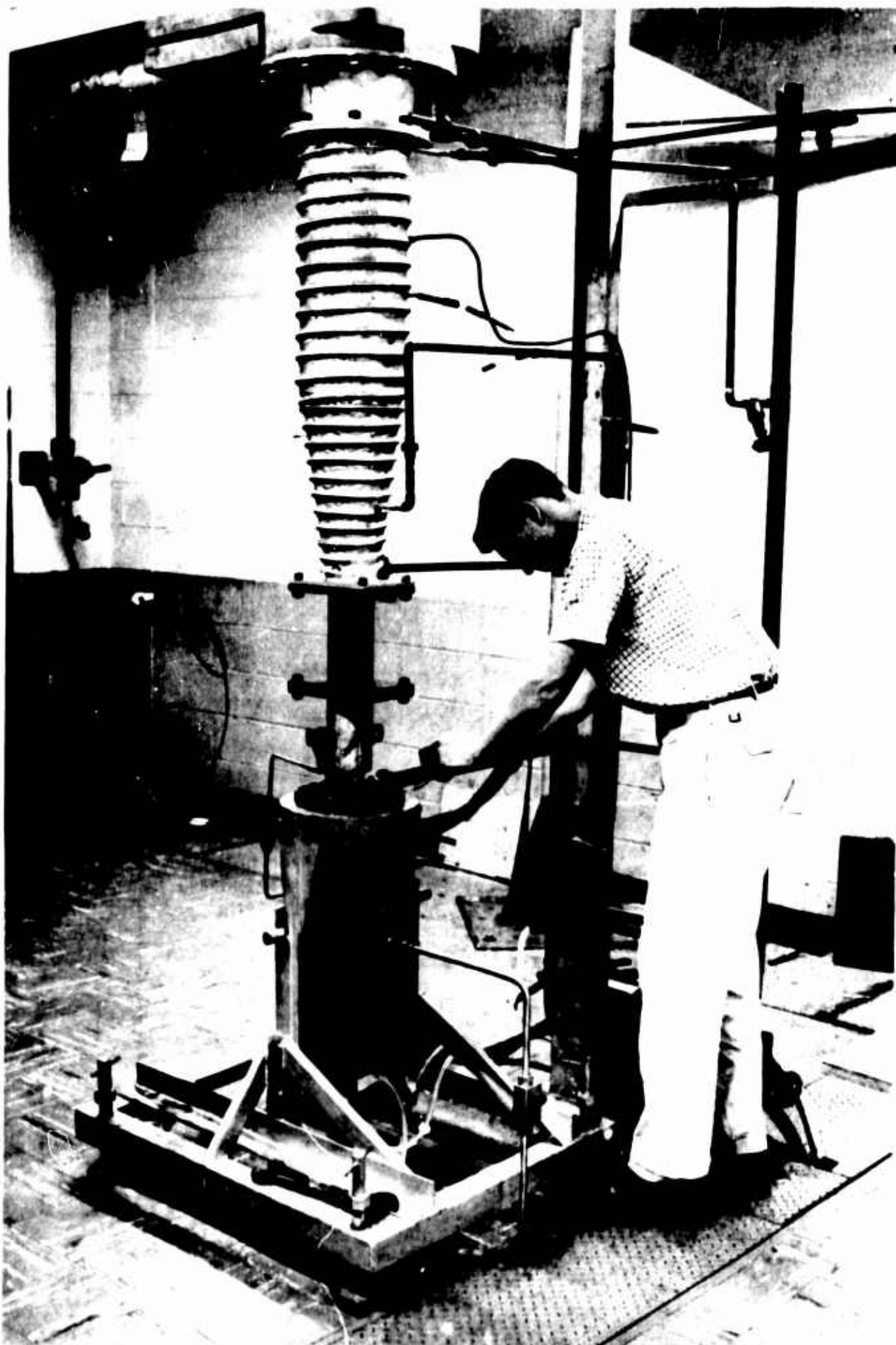
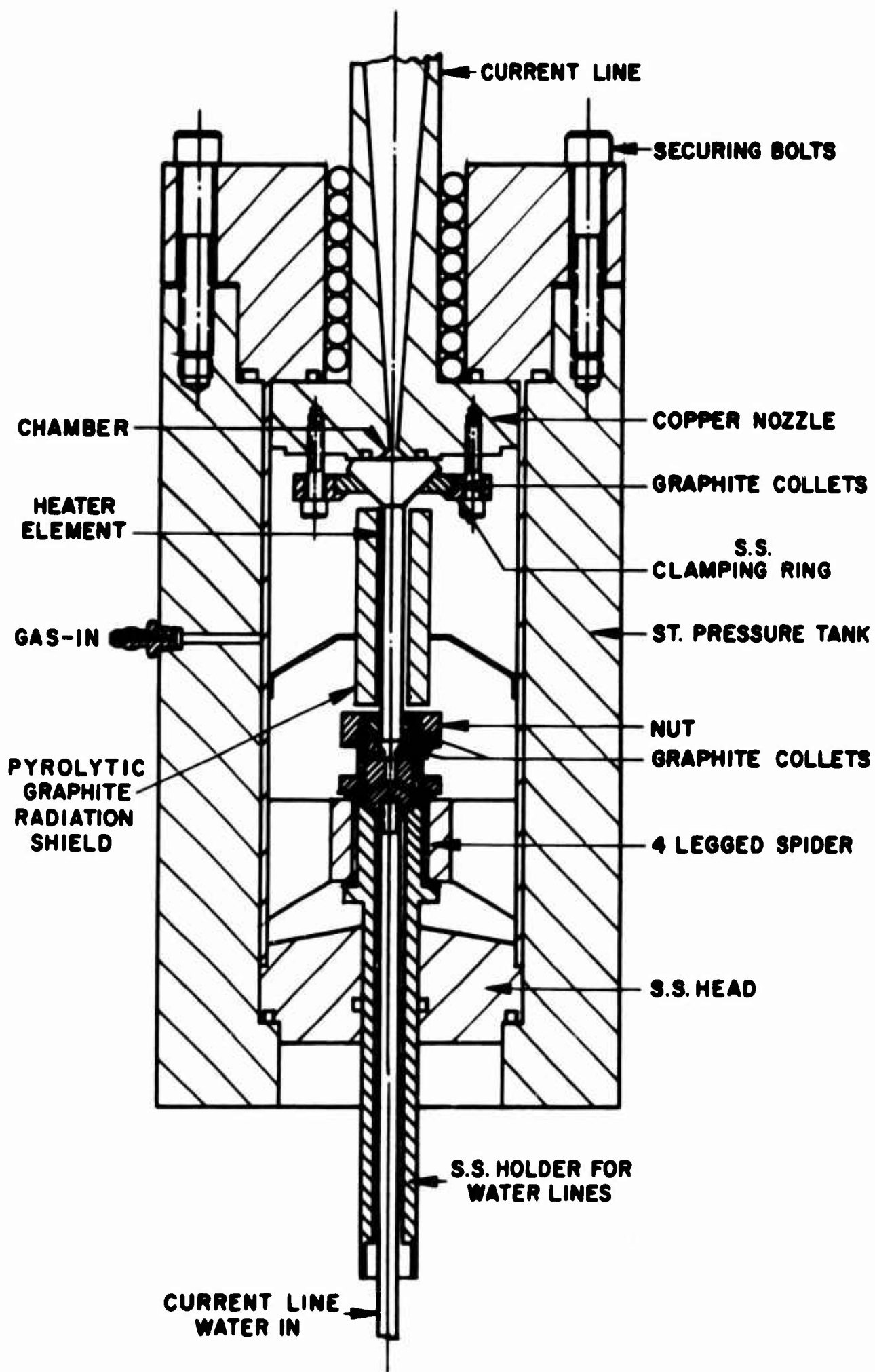


Figure 1. Line diagram of the high pressure, high temperature nitrogen facility



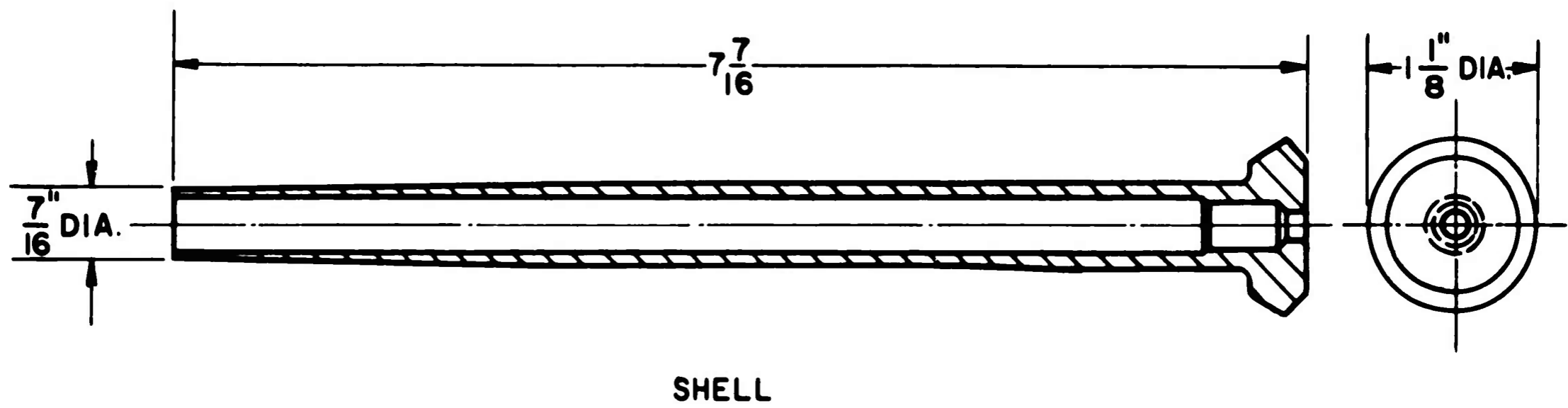
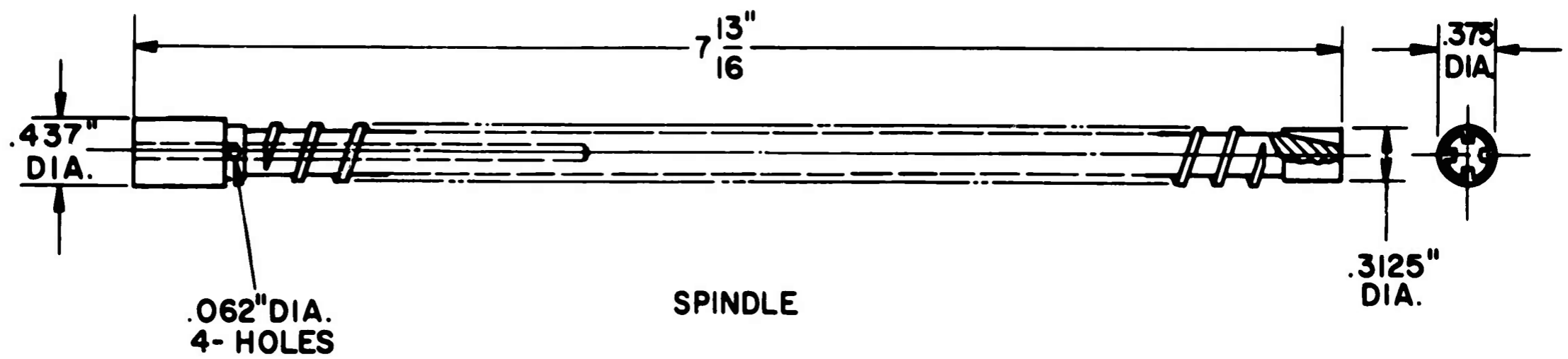
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Figure 2. Photograph of the pressure vessel, nozzle and diffuser cooler



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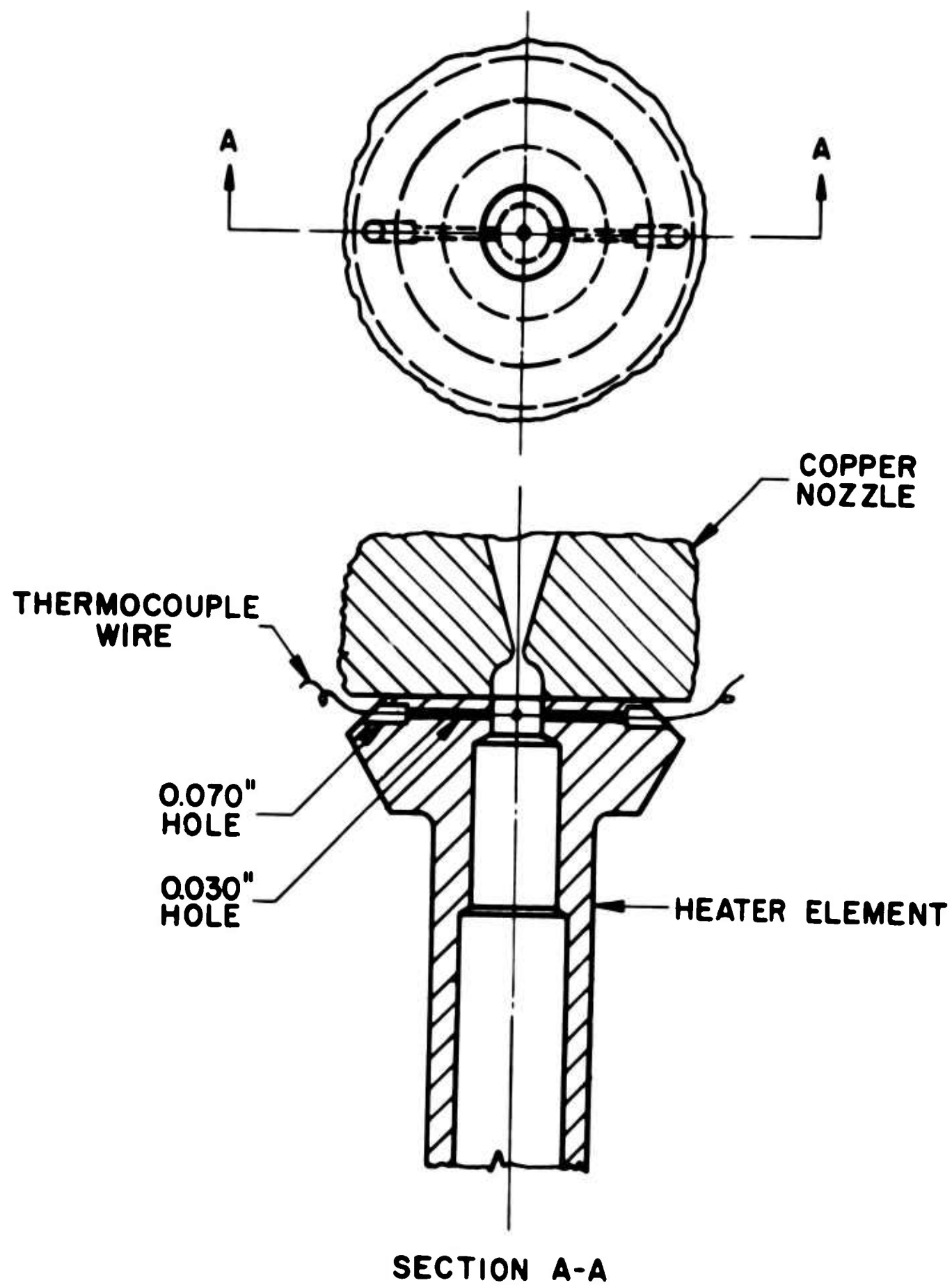
Figure 3. Pressure vessel details



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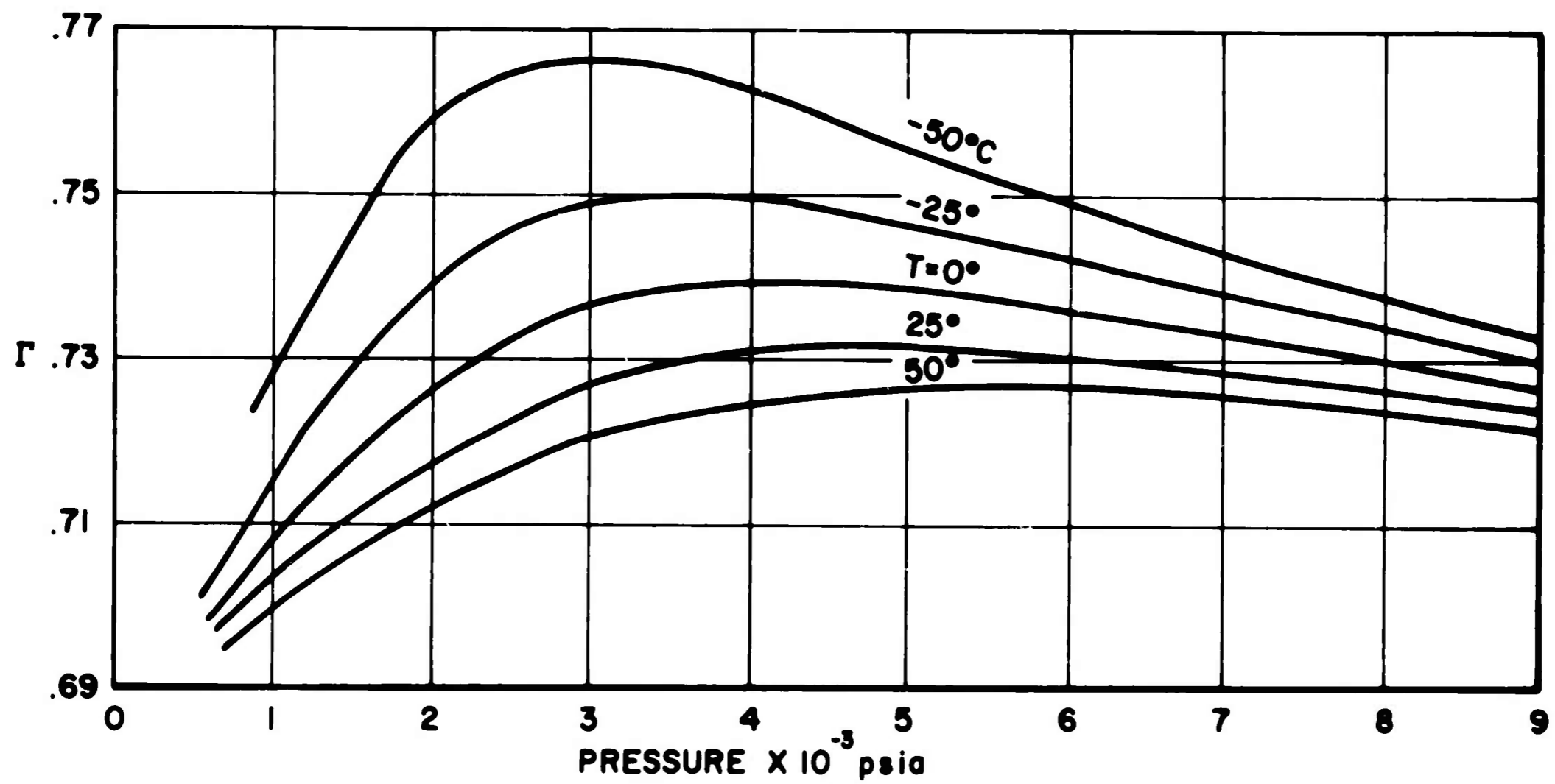
Figure 4. Heater element details.

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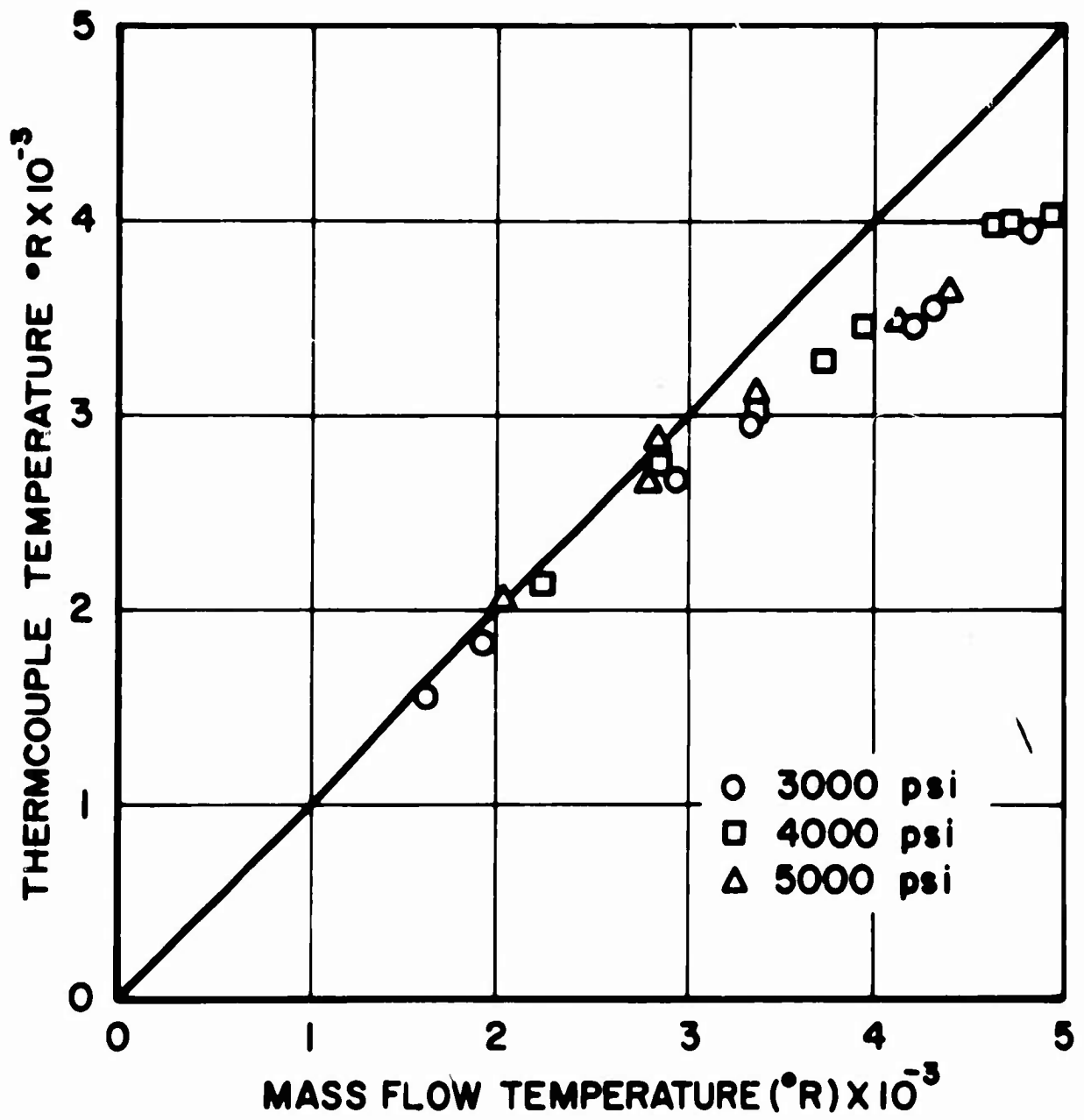
Figure 5. Thermocouple arrangement



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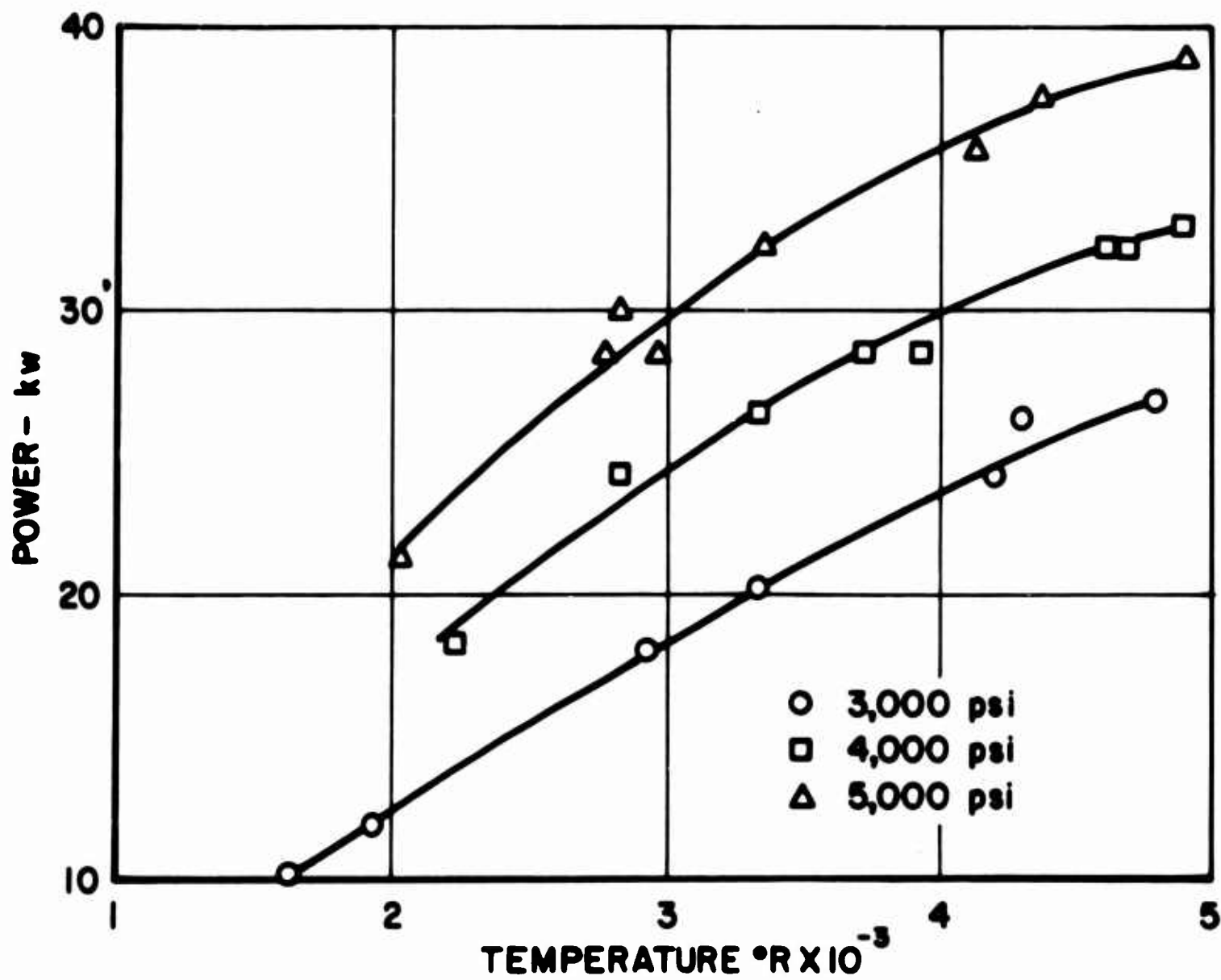
Figure 6. The effect of pressure on Γ at low temperature

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Figure 7. Mass flow and thermocouple temperature measurements



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Figure 8. Power into the heater